First Results of Magnetic Analysis for a High Field Dipole Model.

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I. Introduction

The main goal of this note is to summarize results of a HFD Model magnetic modeling. The dipole cross-section that was taken as a base for the modeling was chosen to be one of several potential candidates that meet the magnet field quality requirements; it has six-cableblock arrangement, 40 mm bore diameter, and use 28-strand IGC-type cable with strand diameter of 1.00 mm. To make a proper choice of a mechanical arrangement of the dipole cross-section, it is useful to realize how magnetic properties like margin field, maximum current, and harmonics content change as a function of excitation current and basic cross-section geometry parameters. The note will provide this kind of information arranged in a way that looks logical and goes form simple ROXIE magnetic field analysis to nonlinear magnetic calculations with the use of OPERA magnetic modeling program. Although the results obtained are neither universal, no final, their analysis will hopefully help to choose final HFD Model cross-section.

II. ROXIE calculation results

The cable data used with ROXIE magnet optimization program [1] can be found in the Table 1 below:

Table 1

Parameter name	Cable parameter value
Cable width (mm)	14.235
Cable thickness (mm)	
thin side	1.6904
thick side	1.9165
Insulation thickness (mm)	
azimuthal	0.1
radial	0.11
Number of strands	28
Strand diameter (mm)	1.01
Cu/SC ratio	0.85
Cabling angle (deg)	14.5
Quench margin parameters	
Temperature (K)	4.2
Magnetic field (T)	12
Critical current density (A/mm^2)	1886
Critical current density slope (A/mm^2/T)	400

Using these cable data, 6-block solution to optimization problem was found using ROXIE program with the central field corresponding to the quench margin B_{cm}= **12.65 T** at I_m = **17.7 kA**. The iron screen internal radius was chosen equal to 60 mm for these calculations leaving only 10-mm gap for a spacer between the coil and screen. It is obvious that, at a given excitation current, if we choose to increase the gap, central field

would decrease. Simultaneously, the field would decrease at cable location that would allow increasing an excitation current to some extend. It means that the central margin field drop will not be so pronounced as the drop of a central field at given current. Said above is illustrated by the chart in Fig. 1 where central field at excitation current 17714 A (B (T)) and central field corresponding to quench margin (Bmar (T)) are built against iron screen internal radius. It is obvious that an increase of central field is only possible with increase of excitation current as it is possible to see from the chart in Fig. 2 below.
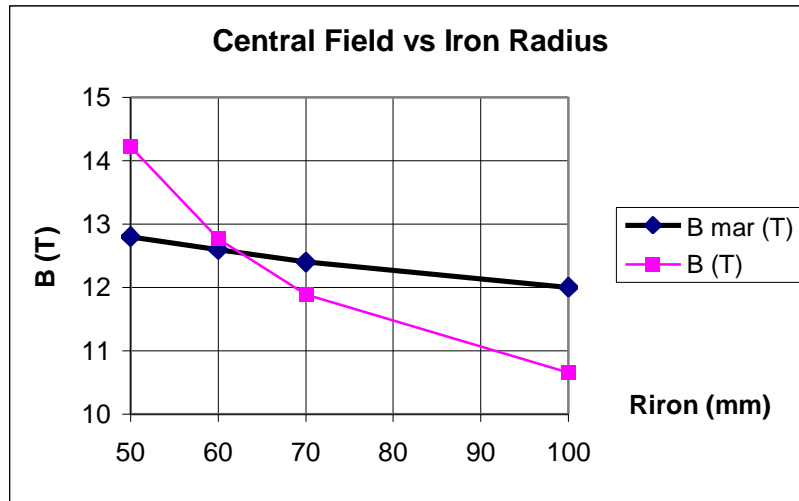
Central Field vs Iron Radius
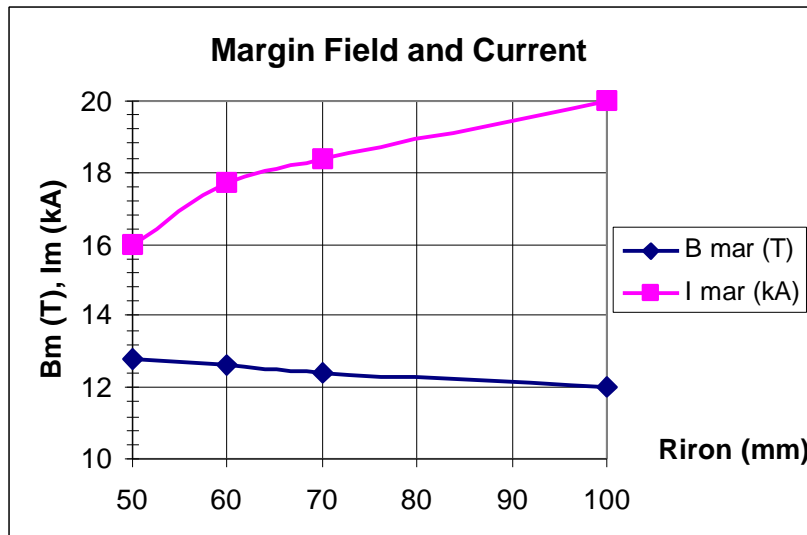
Fig. 1

Margin Field and Current

Fig. 2

Because the available in TD power source is able to provide 18000 A of excitation current only, it is necessary to discuss a possibility to reduce an excitation current if for some reason it is required more than 10 mm gap between coil and iron screen.

The magnetic field harmonics content changes with the iron screen internal radius change. As it is possible to see from the chart in Fig. 3, sextupole b3 drops by about 6 units while gap changes from 0 (50-mm iron screen internal radius) till 50 mm (100-mm

internal radius). Harmonics b5 through b11 do not change significantly, which seems quite natural if to take into the account that the change is governed by a multipole's image in screen; field amplitude generated by a mulitipole decreases with distance quicker for higher multipoles.
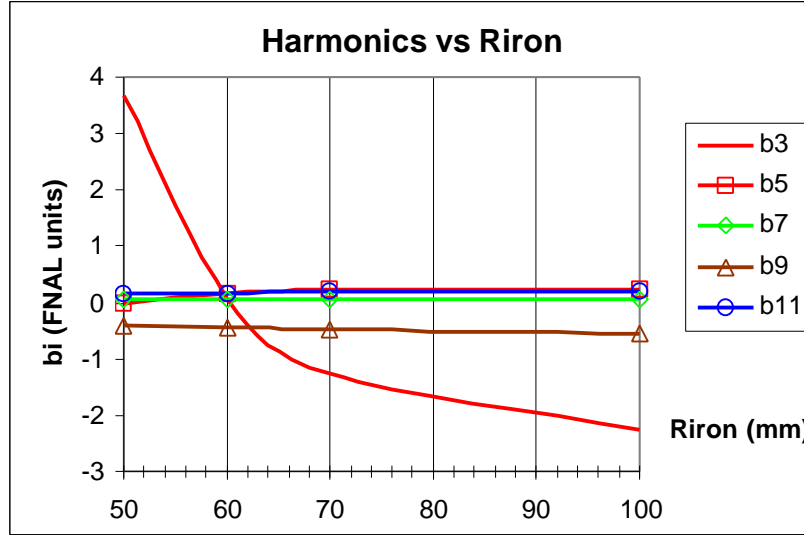

Fig. 3

It is necessary to mention that ROXIE code does not allow at this stage to change outer diameter of the iron screen. Nevertheless it would be interesting to know to which extent the dipole field is sensitive to the external diameter of the screen. It is also necessary to know the dipole fringe field change as a function of screen diameter. These data will help to choose screen diameter optimal from the point of view of assembly technology. It is possible to obtain the information mentioned above with the use of OPERA magnetic modeling program. The use of the ROXIE-generated dipole cross-section in the OPERA input file gives an intrinsic sextupole defect of about 1 unit. The attempt to understand this effect resulted in a reasonable explanation that it is due to different cable current distribution patterns used in the two programs. ROXIE uses current filaments to calculate magnetic field based on Biot-Savart's law; OPERA uses uniform current density through the cable cross-section approach. As a result, because cable has a trapezoidal cross-section, OPERA code gives effective strand current that rises with radius. To fix this defect, modification of the cable cross-section was made to make it rectangular. The result of direct comparison of ROXIE- and OPERA-generated field is summarized in Table 2. The cross-section used for the comparison had ideal, 60-mm internal radius magnetic screen. Excitation current was chosen equal to **17714 A,** which is close to quench margin value. Although there is still difference in b3 value, it is about 0.04 units, which is acceptable. This difference is probably, as before, due to different current representation technique used by the two programs. Four different codes were used to calculate Fourier spectrum of the magnetic field found by OPERA program. All of them have given very close results; so in the Table 2 and further, Fourier spectrum calculations is done using OPERA internal code, which requires calculation of the azimuthal magnetic field component along circular arc.

Table 2

	ROXIE	OPERA
Bc (T)	12.771	12.772
b3	0.063	0.021
b5	0.171	0.165
b7	0.061	0.062
b9	-0.456	-0.457
b11	0.18	0.18
b13	0.01	0.009

III. OPERA analysis results

Magnetic modeling using OPERA shows that the dipole central field almost does not depend on the screen outer radius. It allows using fixed excitation current when evaluating harmonics content change with outer radius. This current was chosen equal to 17.714 kA as earlier in order to compare field drop due to iron saturation effects. Comparison of Fig. 2 and Fig. 4 shows that this drop is about 1 T.
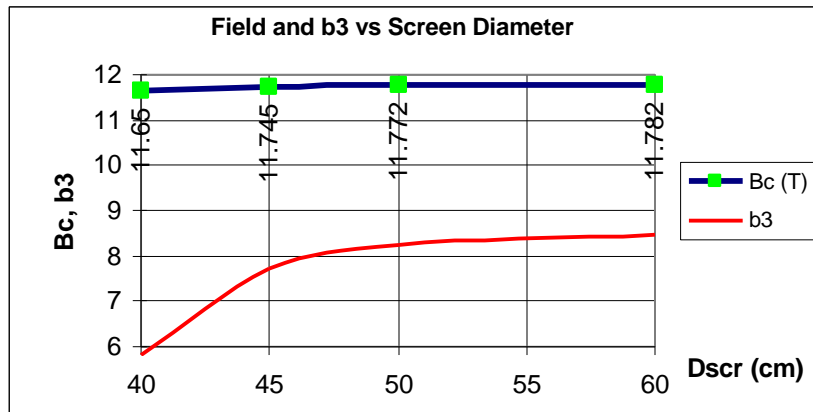

Fig. 4

It is possible to see that sextupole b3 changes significantly only when outer radius becomes rather small, and screen iron is fully saturated in the midplane (see Fig. 5).
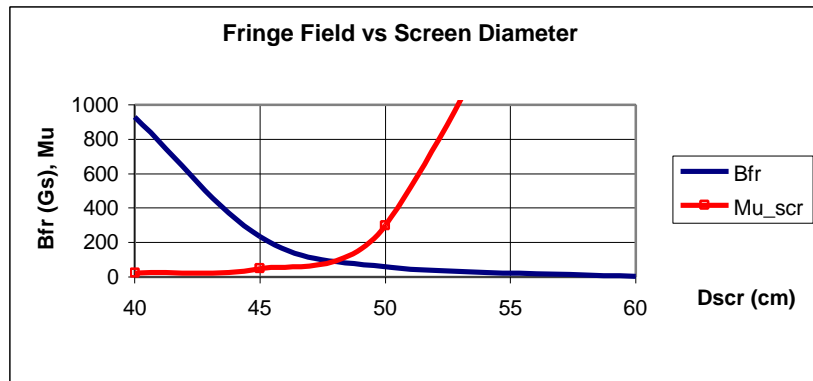

Fig. 5

4

Figure 5 presents the dependence of fringe field and iron permeability in the midplane near the outer border of the screen on the outer screen diameter. If μ < ~25, the iron can be considered fully saturated, and fringe field significantly increases. As it was in linear case with ideal screen, harmonics other than b3 do not change significantly through all the range of the outer diameter change.

As it is possible to see from the charts above, the screen diameter of 500mm gives reasonably low fringe field of 60 Gs near the screen. Nevertheless, it is necessary to mention a possibility to reduce screen diameter, which can be useful to simplify magnet assembly technology. It was shown that it is possible to use 40-mm diameter iron yoke and additional side screen to reduce significantly fringe fields. More over, sextupole does not change to the same extent when one uses an additional screen with 400-mm diameter yoke. It will be necessary to study this problem further to get reasonable requirements for the additional screen location and shape.

Another important subject to study is excitation current effect at one chosen cross-section. Fig. 6 shows the dipole saturation effects and field-current dependence calculated using linear approximation. It is possible to see that the lost of magnetic field due to saturation effects reaches approximately 1 T at maximum current.
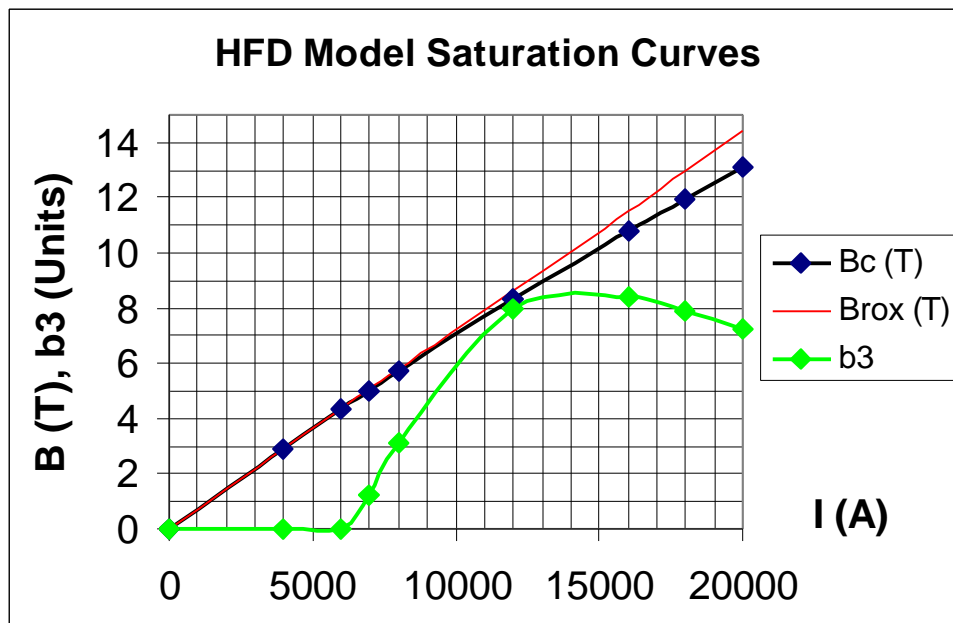

Fig. 6

Harmonics content dependence on the excitation current shows strong sextupole current dependence. Sextupole changes by 8 units when current rises from approximately 6 kA till 12 kA. It will be necessary to find a proper way to compensate this sextupole rise. One of obvious ways is to increase a gap between coil and iron yoke.

Other harmonics are not so sensitive to iron saturation. Only b5 shows a tendency to follow the b3 pattern, but total change for b5 is about 0.2 units.

Maximum achievable field can be found from the saturation curve after we find quench margin current. It is possible to do it if to compare maximum magnetic field that dipole coil cable sees and short sample field limit. Table 3 below shows short sample

current density limit for IGC-type superconductor that will be presumably used to make cable for the HFD model [2]. Current values can be calculated, as we know number of strands, strand cross-section, and Cu/SC ratio (see Table 1).

Tab. 3

B [T]	Jc (A/mm2)	Ic (A)
10	3074	36488
11	2427	28808
12	1886	22387
13	1435	17033
14	1063	12618

Chart in Fig.7 allows us to find both quench current, and maximum central field. As it is possible to see, quench current is about **18.25 kA**, which is slightly higher than available current source allows. Central field that corresponds to this current is as high as **12.15 T**. It is possible to see that the field is about 0.5 T lower than ROXIE prediction, but current required is about 500 A lager.
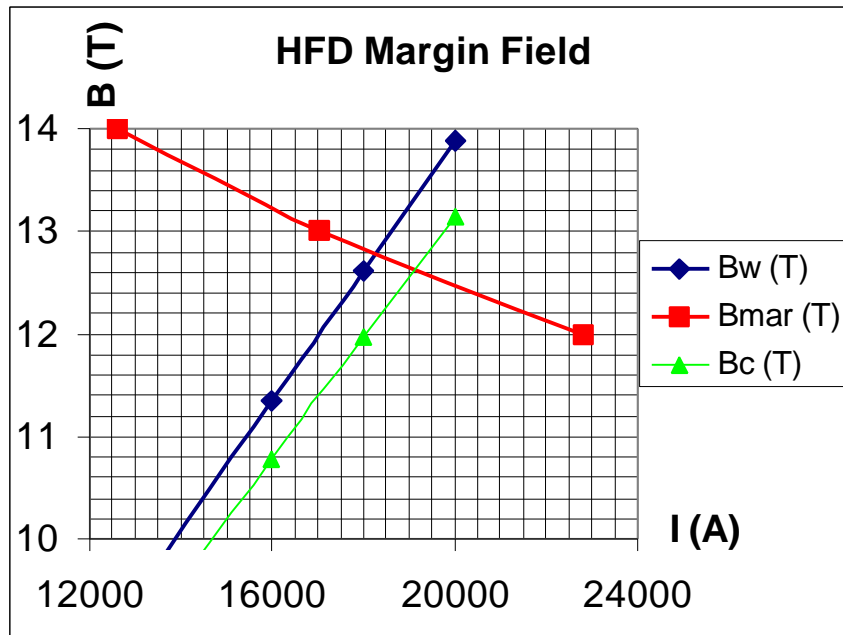

Fig. 7

IV. Conclusion.

The results presented show that magnetic field can reach required level of 12 T with the use of a current source available at TD. Most concern is about the sextupole behavior. Even if not to take into the account superconductor magnetization effects, it will require efforts to solve the problem. Magnetization effects study is imperative for the future study. It is time to make final cable and cross-section choice in order to concentrate efforts on a right subject. Nevertheless, maybe additional loop will be required to get a final choice.